Estimating Winds and Waves from SAR Under Typhoon Conditions

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LONG-TERM GOALS

The long-term goal of this program is to be able to utilize SAR imagery to improve predictions of storm tracks and storm strength at landfall (we use storms as stand-in for hurricanes, typhoons, etc.). This will be done with a system that uses SAR imagery of the storm at sea to estimate wind and wave conditions within the storm, then utilizes these estimates to re-set storm model parameters so that the predicted winds/waves at the time of the SAR imagery match the actual winds/waves. The goal is that the model predictions derived with the re-set parameters will be improved over those that do not have the SAR estimates.

OBJECTIVES

There are three objectives in this program.

(1) Modify the existing General Dynamics Advanced Information Systems (GDAIS) wind vector tool to handle the higher wind states in storms and generate accurate maps of wind vectors within the storm.

(2) Modify the existing GDAIS wave spectra tool to handle the higher wind/wave states of storms and generate accurate maps of wave height statistics within the storm.

(3) Transition the code to CSTARS at the University of Miami to create an automated processing system

APPROACH

(1) Modification of the wind vector tool

Under the NOAA/NESDIS funded Alaska SAR Demonstration Project, GDAIS has developed an algorithm for estimating wind vectors from SAR imagery (Wackerman et al., 2003). Wind directions come from a projection-based method to find linear features in the SAR image that are aligned with the wind. Wind speed comes from inverting a physics-based forward model for the RCS that uses the two-scale model to predict mean RCS values (Wackerman et al., 2002). The forward RCS model already has a tilted Bragg scattering term (so there is no linearization of the tilted ocean surfaces), a hydrodynamic modulation term that induces an upwind, downwind asymmetry as seen in observations, a spectral scattering term for wave facets tilted toward the radar, and a choice of possible wave spectral models to use. This model has already been validated for C-VV and C-HH data (Wackerman et al.,

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2002) and is currently being validated for X-band VV and HH data as part of a set of airborne SAR collections. First we propose putting into this forward RCS model a wave height modulation model appropriate for typhoon conditions; i.e. a model where the wave heights grow appropriately with the strong winds. Second, we currently assume a zero-mean Gaussian distribution for the wave facet tilts where the standard deviation is modeled based on wind speed. The model for slope variance with respect to wind will need to change for typhoon conditions, and we will need to examine whether the Gaussian assumption is still correct (essentially whether the waves are dominantly non-linear). Theoretically the rest of the forward model should work as is. We will compare the resulting forward RCS model with CMOD4 and CMOD5, as well as validate it against the test set discussed below (note that we can validate the forward RCS model separate from validating the wind or wave tools).

The wind direction estimation will most probably also need to be modified to handle the smaller spatial scale of significant changes in wind direction for typhoon conditions. Currently the projection code assumes a relatively large spatial scale (~16km) for wind direction changes. We anticipate that this will be performed by changing the metric used to determine which projection has the largest variation across spatial scales (and thus represent the direction that is orthogonal to the wind vector). Currently this is done by finding the direction of maximum contrast (standard deviation divided by the mean). We may not have enough samples to generate accurate statistics over the short spatial scales, so we anticipate needed a metric based on more point-line measurements (e.g. maximum minus minimum value, or the maximum local gradient).

(2) Modification of the wave spectra tool
Also under NOAA/NESDIS funding, GDAIS has developed an automated wave spectrum estimation tool based on both linear transfer function (Wackerman, 2006) as well as a fully non-linear transfer function that iteratively finds the underlying wave spectrum from a starting assumption of no waves (thus no a priori wave information is required). We anticipate needing the fully non-linear transfer function for typhoon conditions. However this forward model has an internal wave-to-RCS transfer function that is probably not appropriate for typhoon conditions. We proposed modifying this by incorporating the forward RCS model from the wind vector tool into the wave estimation tool to allow accurate RCS modulations from typhoon-condition waves. All the non-linearity of the SAR imaging process should then work as currently implemented. This will require modifying the iteration process which uses a gradient estimate to perform a conjugate gradient search for the wave spectra that minimizes errors with the SAR image. We will need to re-derive this gradient using the new forward RCS model.

(3) Transition to CSTARS
The SAR working group will decide upon the formats and I/O specifications for the system and we will modify our code to conform to them. We will then install the code at CSTARS and perform testing and validation.

WORK COMPLETED

This program is finished and all the work has been completed.
(1) Modification of the wind vector tool
A new wind vector estimation tools was developed for typhoons that consisted of three components: (a) automated eye location; (b) automated wind direction estimation; and (c) automated wind speed estimation. The eye location software was a new component developed this year. The wind direction software was a modification of previous code that was based on finding the projection direction that

maximizes the contrast of the image. For typhoons we had to add a transformation that removed the radial direction in order to allow smoothing over large spatial scales, and to add a component that used the eye location to remove errant wind directions. The resulting directions were validated using historical SAR imagery with coincidence QuikSCAT observations of wind direction. The wind speed estimation required the development of a new forward model (often referred to as the Geophysical Model Function) due to issues with the standard CMOD5 model involving locations where the SAR image radar cross section is too high for the CMOD5 model and involving locations where CMOD5 gives multiple solutions. The resulting wind speeds were validated using historical SAR imagery with coincident QuikSCAT and SFMR observations of wind speed.

(2) Modification of the wave spectral tool

A new wave spectrum estimation code was developed for typhoons that modified an existing code to deal with the longer wave length waves and, more importantly, to automatically determine when wave modulations were not present in the SAR image. This latter component was important since the SAR imagery used to monitor typhoons is often of very coarse resolution (in order to gain spatial coverage) and thus does not always image the ocean waves. Validation data for waves in typhoons is difficult to come by, so to date we have validated based on model results (from the WAM and SWAN models)

(3) Transition to CSTARS

All of the code has been transitions to CSTARS and incorporated into their system. It has been tested and has been running on the 2010 ITOP field experiment data.

RESULTS

A historical data set of SAR images over typhoons in the Pacific and hurricanes in the Atlantic was provided as part of the RADARSAT Hurricane Applications Project (RHAP) and a subset were selected as the test set for the SAR ITOP working group. The working group then collected a set of ground truth data for these images consisting of: (1) QuikSCAT data that had been shifted along the storm track to coincide with the SAR image collection time; and (2) SFMR flights that had been shifted along the storm track to coincide with the SAR collection time. The QuikSCAT data provided wind direction and wind speed. The SFMR data provided only wind speed, but at a much higher spatial resolution than QuikSCAT.

Figure 1 shows the comparison of SAR-derived wind directions from the final software system with QuikSCAT wind directions for all test set data. Only QuikSCAT observations that had not been flagged as rain contaminated were used in these

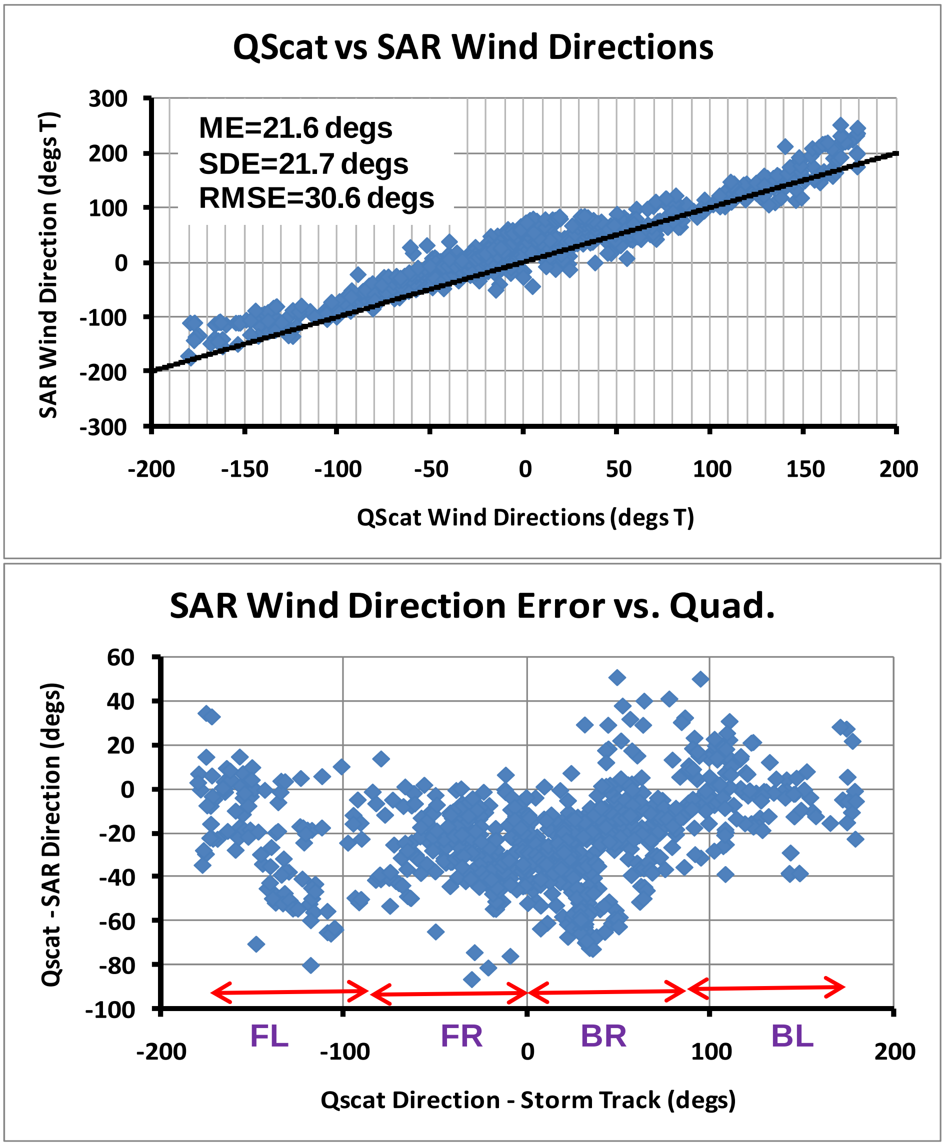

Figure 1: Comparison of SAR-derived wind directions to QuikSCAT observations over the whole test data set of historical storms. Top plot indicates that is an overall mean error in wind direction of ~ 20 degrees which indicates that the QuikSCAT surface winds are rotated inward by 20 degrees compared to the ocean surface features that the SAR uses for wind direction. Bottom plot shows the error between SAR and QuikSCAT directions as a function of the quadrant of the storm (forward-left (FL), forward-right (FR), back-right (BR), back-left (BL)). There is some indication of a change in bias with quadrant.

comparisons. The top plot shows SAR-derived directions versus QuikSCAT directions with the error statistics shown in the plot. The interesting result here is that there appears to be a rotation between the SAR surface features that are used to estimate wind direction and the QuikSCAT surface wind directions of about 20 degrees. This rotation is always inward toward the eye, indicating that the surface winds have more inflow than the ocean surface features imaged with the SAR. If we remove this bias, the resulting RMSE is 22 degrees. The bottom plot in Figure 1 shows the error between the SAR and QuikSCAT directions versus the difference between the storm propagation direction and the QuikSCAT wind direction. This gives us the ability to divide the errors into storm quadrants; these regions are shown in the bottom of the plot as forward-left (FL), forward-right (FR), back-right (BR) and back-left (BL). There is some indications that this direction bias exists to the right of the storm track and not the left. However in the final system we just treated this as a constant offset in angle.

Figure 2 shows example wind speed products (with the wind directions overlaid as white arrows) for two of the Pacific storms in the test set. The wind speeds were derived from a new GMF that was developed in this program called CWaR4 that was based on an analytical two-scale scattering model (Wackerman et al., 2002) that was empirically scaled to match the standard CMOD5 model. Figure 3 shows the SAR-derived wind speeds versus QuikSCAT wind speeds for the entire test set. The Pacific storms are the right two plots and the Atlantic storms the left plots. The top plots are for the GMF derived in this program (CWaR4) and the bottom plots are for the standard CMOD5 GMF. Error statistics are shown on the plot. For these comparisons, all of the QuikSCAT wind speed values were used even if they had been flagged as rain contaminated. This allowed us to get the higher wind speeds from QuikSCAT, and it is generally thought that the wind speeds are good in the rain regions even if the directions are not. Note that the CWaR4 results are slightly better than the CMOD5. Overall we can estimate wind speed with a RMSE of 4 – 6 m/s.

Figure 4 shows SAR-derived wind speeds versus SFMR wind speed observations for 3 Atlantic storms for which we have SFMR coincident flights. SFMR generates wind speeds at much higher spatial resolution than QuikSCAT. For these comparisons we actually averaged the SFMR wind speeds down to a 1 km spacing (note that QuikSCAT provides wind speeds on a ~25km spacing). The software appears to perform better on the SFMR data than the QuikSCAT; RMSEs are around 3 – 4 m/s. Also note that CWaR4 appears to perform better than CMOD5.

However, all is not solved yet. There was one storm (Katrina on 08/28/2005) that did not work well. Figure 5 shows the same plots as Figure 4, but the additional green points are for this Katrina storm. Note that CWaR4 does a very poor job, and indicates a fair amount of saturation in wind speed. CMOD5 does much better. We anticipate addressing these concerns in follow-on programs.

We did not have much ground truth data for the wave estimation validation, we only had model runs from one of the Atlantic storms (Helene). In addition, the coarse resolution imagery did not often image the wave modulations. Figure 6 shows two example wave

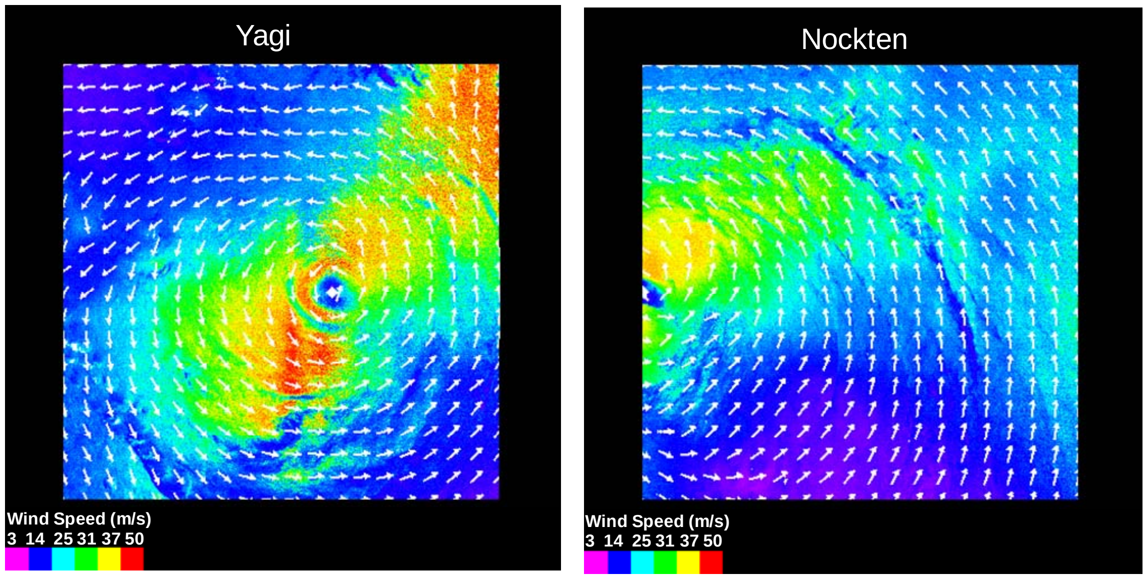

Figure 2: Example wind vector products for two Pacific storms. White arrows areSAR-derived wind direction. Colors are wind speed (legend is at the bottom-left)

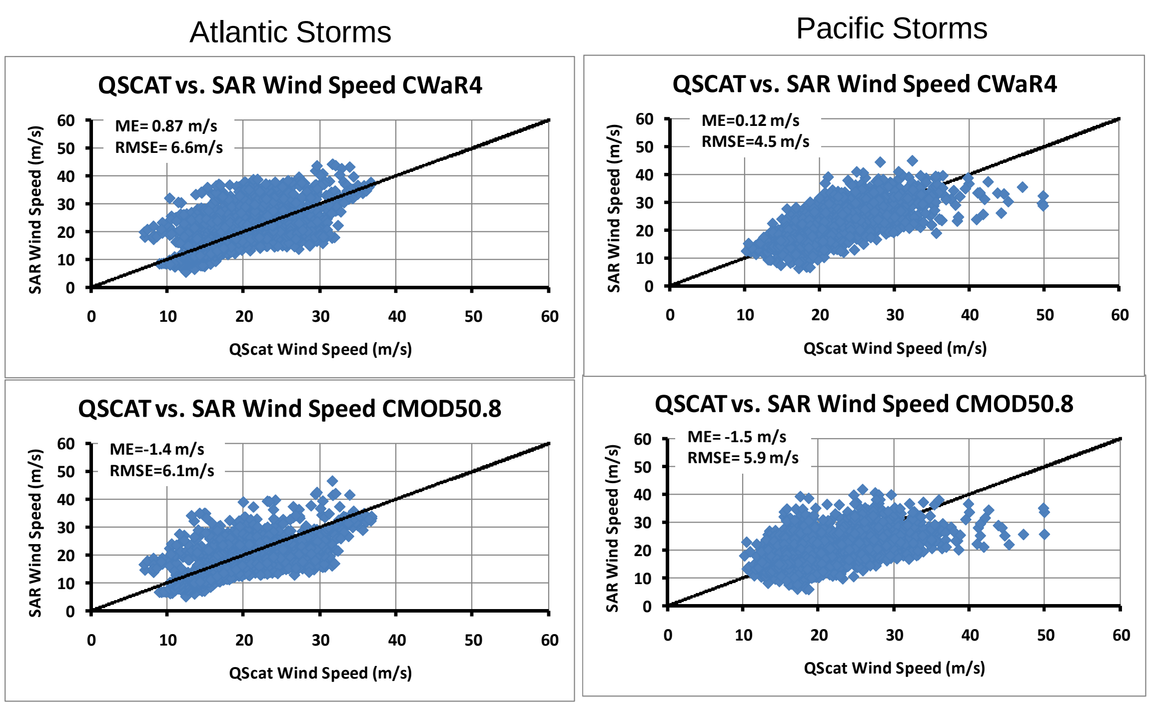

Figure 3: SAR-derived wind speeds versus QuikSCAT for Atlantic (left) and Pacific (right) storms using the new CWaR4 GMF (top) versus the standard CMOD5 (bottom). Note that CWaR4 performs slightly better.

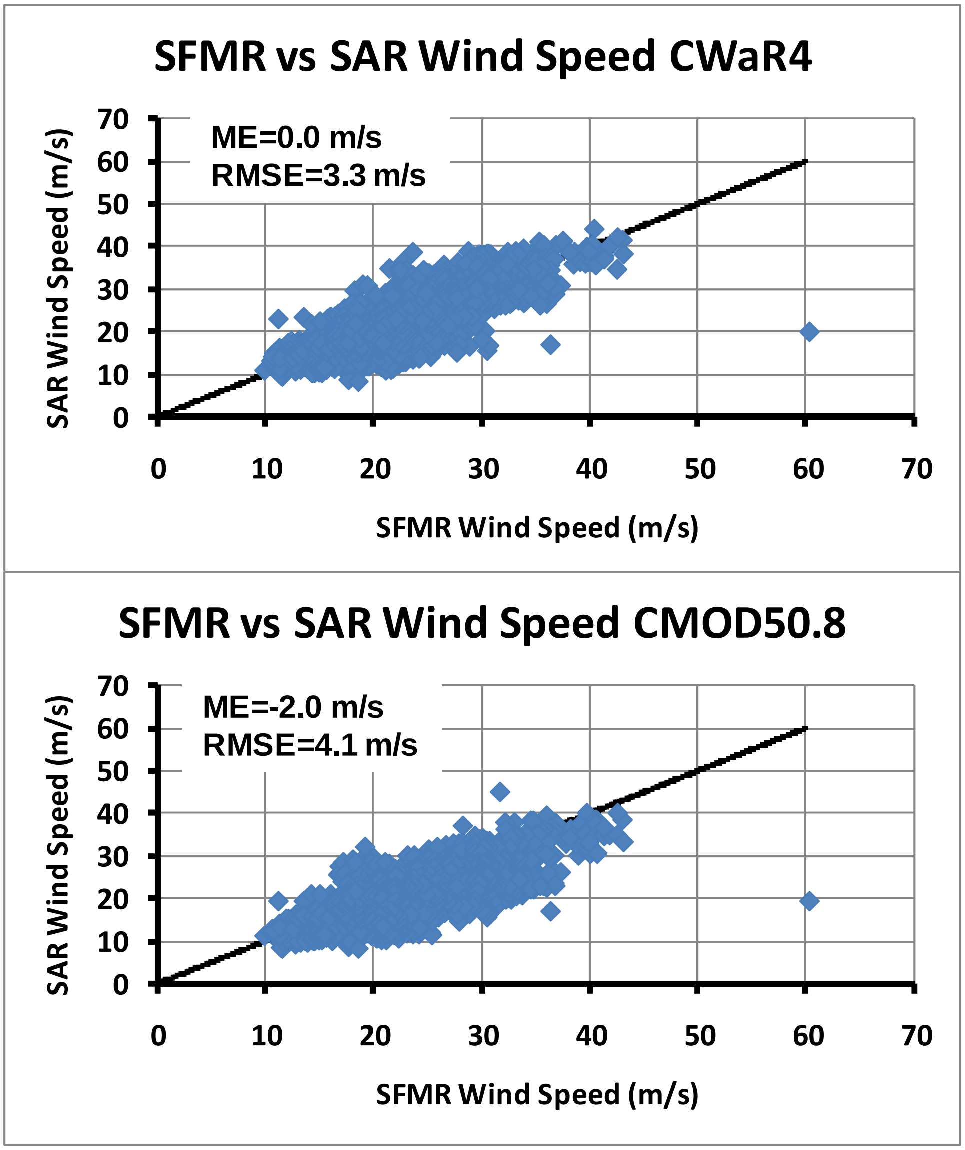

Figure 4: Comparison of SAR-derived wind speeds to SFMR observations for 3 Atlantic storms. The new GMF (CWaR4) is on the top and the standard model (CMOD5) is on the bottom. Note that CWaR4 performs slightly better (however see Figure 5).

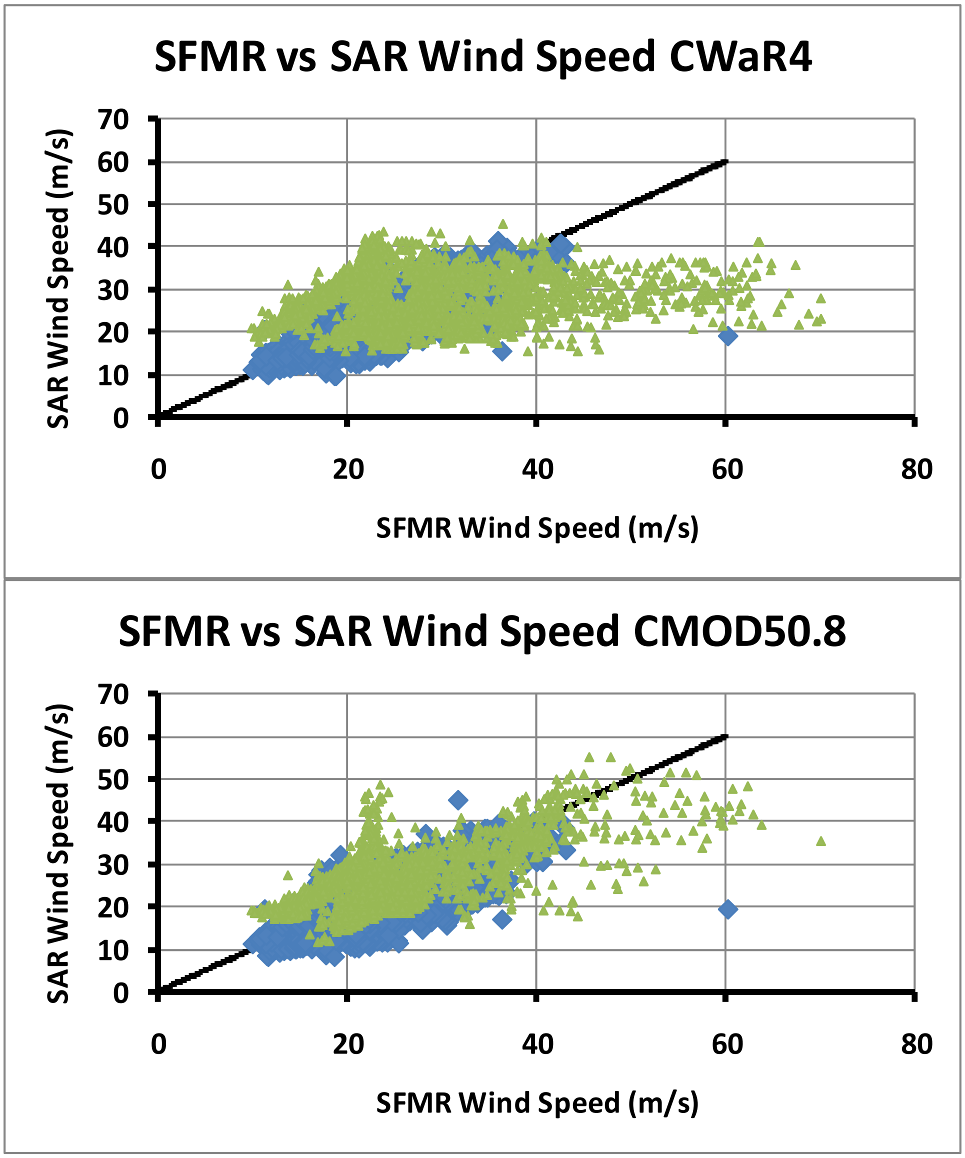

Figure 5: Same as Figure 4, but the green points are for the storm Katrina on 8/28/2005. For this storm CWaR4 (top) saturates at around 40 m/s while CMOD5 does not.

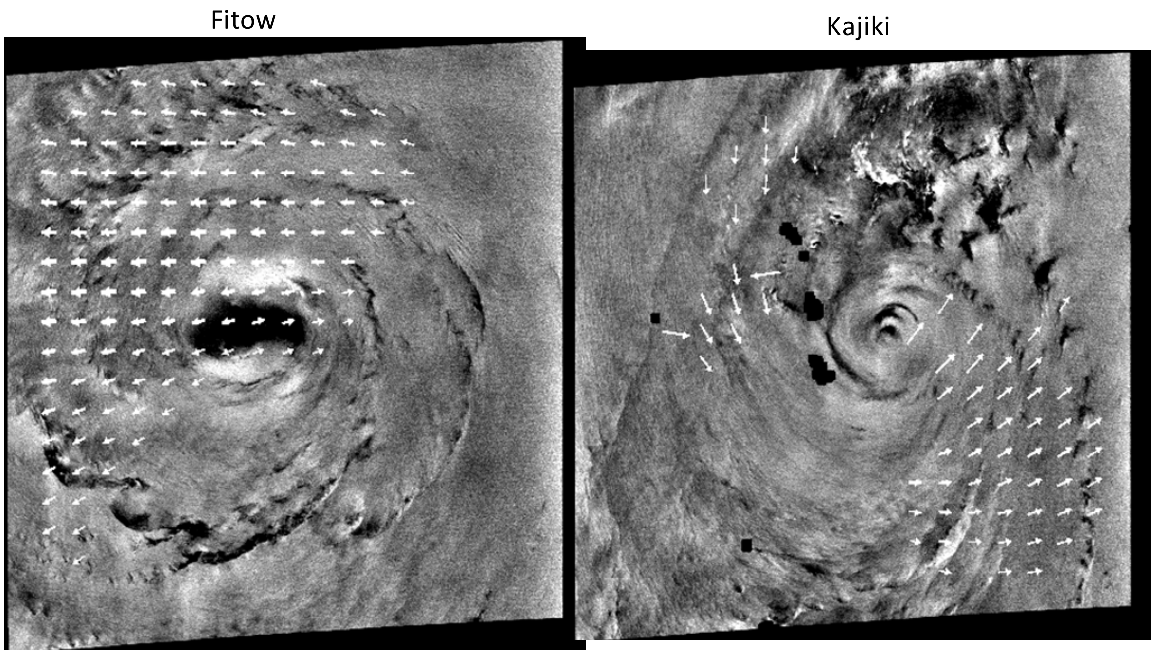

Figure 6: Example wave products for two of the Pacific storms. Underlying image is the SAR image after flattening and contrast-stretching. White arrows represent wave spectra statistics: direction is mean wave direction, length is mean wave length, thickness is significant wave height. Note that the SAR only images the longest waves due to the coarse resolution.

products for two of the Pacific storms. The underlying image is the SAR image (flattened and contrast-stretched) and the white arrows indicate wave spectral statistics: arrow direction is mean wave direction, arrow length is mean wave length, arrow thickness is significant wave height. Note that we only image waves in a portion of each SAR image. Figure 7 shows a comparison of the SAR-derived wave information and WAM model runs for one of the storms. Note that they are similar away from the eye, but it is not clear what is happening around the eye with the model results. We anticipate continuing this work on follow-on programs.

The entire system has been transitioned to CSTARS and has been running as part of the ONR ITOP field experiment.

IMPACT/APPLICATIONS

If successful, the resulting system may significantly improved predictions of storm tracks and storm strength at landfall. This would have a large impact on coastal regions.

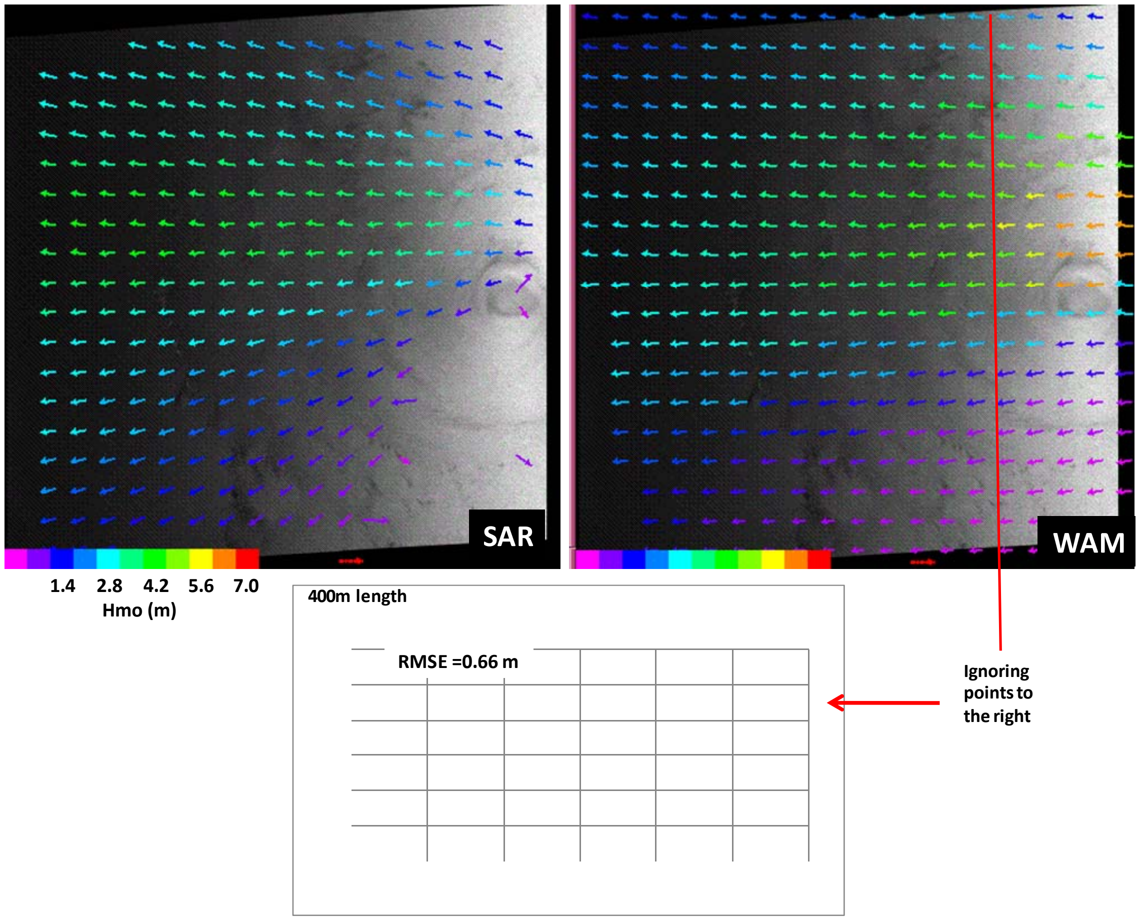

Figure 7: Comparison of SAR-derived wave statistics (left) to WAM model results (right) for Helene on the 19th. For these products the color of the arrow encodes significant wave height instead of the thickness. Note that away from the eye they agree well – bottom plot compares their significant wave heights. However near to the eye there are still issues.

RELATED PROJECTS

There are no ongoing related projects that are closely identified with this project.

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